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TAKING DATA IN SUPPORT OF PANEL REDESIGN

by

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INTRODUCTION

Limited techniques are available to assist in preliminary instrument panel design or optimization of an existing panel design configuration. The primary criterion that is currently being used for equipment arrangement is dependent on one or more of the following basic principles: (1) how important the instrument is, (2) the degree of relative use of the instrument, (3) the grouping of similar instruments together, and (4) the degree of related sequential use. Data gathering techniques utilized are usually either direct or recorded observations of movements, user interviews or information received from questionnaires. The majority of effort on visual sampling of displays and on eye movement has been conducted in support of aircraft instrument panel layout. Panel arrangement and pilot instrument scanning became critical with the advent of high speed aircraft and when, due to the state-of-the-art capability, more sophisticated instrumentation evolved in response to more stringent system requirements.

Commonly utilized link analysis techniques provide information which can be applied toward solving two system problems: optimal arrangement of men and machine and optimal instrument panel design (Chapanis, 1959). By utilizing a flow diagram the links between various components are expressed in statistical terms. The analysis is of greatest value in solving problems of layout and arrangement. Two classes of links can be considered: functional and sequential. The functional links are first order approximations based on frequency of eye fixation or the importance of the connections between men, or between men and the equipment components in question. They are the statistical probabilities indicating

how much a particular connection between men, or men and equipment takes place, for example a proportion of total eye fixation on an instrument. The second order approximation sequential links relate to human movements between equipment components, reflecting the frequency of the relationship and are a statistical indication of how equipment components are related and the dependence of one on the other.

Link values in operational procedures are often derived by a graphic approach in which the sequential steps in the operation are recorded. A graphic method was utilized by Jones, Milton and Fitts (1950) in their classic study of the layout of aircraft instruments. The basic data were obtained by using a motion picture camera that recorded the sequence of eye movements made by numerous pilots during various flight maneuvers. From the data, sequential link values between the instruments were determined (% of eye shifts between instruments). Functional link values were also calculated showing: average length of eye fixation, number of fixations per minute and proportion of time spent on viewing each instrument.

The information from the study was utilized to develop the standard primary aircraft instrument arrangement now found in most aircraft. The basic concept called for the most frequently used instruments to be mounted in the center of the panel. Instruments with high link values or sequential transitional probabilities should be located adjacent to the central instruments. This arrangement minimized required pilot eye movements. The contribution of the link analysis is in providing suggested ways for arrangement that will assist in optimizing the panel design (Chapanis, 1959).

Senders (1964) later demonstrated that the sequential link probabilities were predictable on the basis of the individual instrument fixation probabilities. Knowledge of the fixation probability, p_i , which can be estimated by the relative sampling frequency of the display, enables the approximate calculation of the link value, p_{ab} , between two instruments, a and b, by the formula

$$p_{ab} = \frac{2\,p_a p_b}{1 - \sum_{i=1}^{n} (p_i^2)}$$

where n = number of instruments on the panel.

Application of this theory to the study made by Jones, et al provides results which are in substantial agreement for instruments scanned most frequently (those of prime importance). Greatest variability was found for instruments with low fixation probabilities. This predictability theory is considered valid for laying out an instrument panel design.

McRuer, et al used the prediction technique of Senders to predict the link values for an aircraft Integrated Landing System (Frost, 1971); two recommended panel designs evolved from the predictions. Both designs were found to be substantially the same configurations adopted independently by two airlines and certified by the Federal Aviation Administration. The use of the prediction technique has developed as a useful tool in preliminary design work.

In complex systems which have many components, a quantitative approach utilizing linear programming might be justified. This approach is a statistical method that results in the optimization of some criterion

or dependent variable by manipulation of various independent variables (McCormick, 1970). The Freund and Sadosky (1967) report often cited in human-factors literature presents several types of arrangement problems which in common involve two independent criterion measures: (1) frequency of use of each control or display instruments and (2) an error score for each available area or position of the panel. The goal is to assign each component to a specific position so as to satisfy an objective function of the form

$$\text{Minimize} \quad \sum_{i}^{c} \sum_{j}^{m} f_i e_j$$

where f_i is the frequency of use of display i and e_j is the absolute of relative errors attached to position j.

While a moderate amount of work has been conducted on the development of link value concepts and on their use in panel redesign, virtually no work exists on determining stable estimates of probabilities and link values for use in panel redesign, an important problem in the engineering effort. If data are gathered in a preliminary configuration, in a simulator, or other similar system, then these data can be applied to the engineering redesign effort. While it is true that the redesigned system may cause some changes by virtue of the fact that it has been changed, it is probably true in most cases that this effort will provide a system superior to one based strictly on intuition or design hunches.

There are many known applications of data stability and record length estimation used in engineering. However, a literature search conducted indicates a total lack of information on the stability of human

operator eye movement data and estimation of record lengths to obtain certain desired accuracies in the estimate. It is the intent of this research to provide information that is pertinent to these areas. In conducting this research effort first order probabilities will be considered. It is demonstrated in Appendix A and was previously discussed in Senders' work that in most cases accurate estimates of second order probabilities can be obtained from first order probabilities. Nothing in the development of this research is intended to restrict its generality in application. The techniques used herein can be applied to any engineering effort investigating optimizing an instrument panel design.

Once a model has been developed it should provide a general technique for handling the optimum design and layout of any sort of instrument panel utilized in a dynamic man-machine system. For optimum system design as viewed from the life cycle standpoint in the system engineering process the most powerful tools available must be employed. It is the object of this research to provide additional tools for the system and design engineer to assist them in the development of optimum instrument panel configurations early in the design process.

THEORETICAL MODELS FOR ESTIMATING RECORD LENGTH

Only recently has a theory been proposed on the determination of record length estimation for taking data in support of a panel redesign. The procedure developed is based on the assumption that eye fixation probability estimates for fixed length segments of time follow a normal statistical distribution (Wierwille, 1973). There is no known previous examination of the problem of record length estimation for taking data in support of a panel redesign.

Normal Model

The central limit theorem states: If $\bar{x}$ is the mean of a random sample of size n taken from a population having the mean μ and the finite variance σ^2, then

$$z = \frac{\bar{x} - \mu}{\sigma/\sqrt{n}}$$

is the value of a random variable whose distribution function approaches that of the standard normal distribution as n approaches infinity. When the sample mean $\bar{x}$ is used to estimate the mean of a population chances are slim that this estimate is exactly equal to the mean μ. The error, $|\bar{x} - \mu|$, is the difference between the two quantities. Using the fact that for large n the random variable $\frac{\bar{x} - \mu}{\sigma/\sqrt{n}}$ has a distribution approximately that of the standard normal, it can be stated with a probability of $1 - \alpha$ that

$$-z_{\alpha/2} < \frac{\bar{x} - \mu}{\sigma/\sqrt{n}} < z_{\alpha/2}$$

where $z_{\alpha/2}$ is such that the normal curve area to its right equals $\alpha/2$ (two sided). Therefore, by estimating μ by means of a random sample of size n it is stated with a probability of $1 - \alpha$ that the error $|\bar{x} - \mu|$, is less than $z_{\alpha/2}\ \sigma/\sqrt{n}$ for large values of n. Rearranging the double inequality, the confidence interval of μ having the degree of confidence $1 - \alpha$ can be found from the equation

$$\bar{x} - z_{\alpha/2} \frac{\sigma}{\sqrt{n}} < \mu < \bar{x} + z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \ .$$

Thus it can be claimed with a probability of $1 - \alpha$ that the interval from $\bar{x} - z_{\alpha/2}\frac{\sigma}{\sqrt{n}}$ to $\bar{x} + z_{\alpha/2}\frac{\sigma}{\sqrt{n}}$ contains μ .

It must be absolutely clear what is meant by the previous statements pertaining to the claim that with a probability of $1 - \alpha$ that the interval contains μ . Since the mean of the given population either is or isn't contained in the interval it is not reasonable to address the probability of such an event. What is meant however is that in repeated sampling a confidence of α percent of the confidence intervals obtained will contain the mean of the population. Thus one will obviously not know with certainty if the population mean is contained in the confidence interval but it is known with certainty that when this procedure is utilized to obtain the interval estimates, it is α percent reliable. As an example, if a random sample of size n = 100 is taken from a population having $\sigma = 5.1$ and we obtain a mean of 21.6, then 0.95 confidence interval for μ is given by $21.6 \pm \frac{1.96\ (5.1)}{100}$, providing an interval from 20.6 to 22.6. Here we claim that the interval from 20.6 to 22.6 is a 0.95 confidence interval for the mean of the population is that in repeated

sampling 95 percent of the confidence intervals obtained contain the mean of the population (Miller and Freund, 1965).

It is often desired and a design requirement to calculate the sample size required to reduce the confidence interval a given percentage. In general, the variance of the sample mean decreases as $\frac{1}{n}$, and the standard deviation decreases as $\frac{1}{\sqrt{n}}$. Therefore, the confidence interval shrinks as $\frac{1}{\sqrt{n}}$, and the following relationship applies

$$\frac{z_{\alpha/2} \frac{\sigma}{\sqrt{n}}}{\sqrt{n_{new}}} = \frac{(\bar{x})(\%\text{ reduction of confidence interval})}{100\sqrt{n}}$$

where

$$(\bar{x})(\%\text{ reduction of confidence interval}) = \text{tolerance of the mean.}$$

The application of Wierwille's theory to data taking in support of panel redesign assuming a normal distribution, where the data mean and variance are assumed to be without error, follows the sequential steps:

1. From a sample of data break the data into n observation intervals of equal length t seconds.

2. Select a typical variable say p_2 (instrument number 2 fixation times) on which to apply the theory.

3. Calculate the sample probabilities, ${}_ip_2$, where i=1 through the n observation intervals.

4. Calculate the sample mean for the n samples from the relationship

$$\bar{x} = \frac{\sum_{i=1}^{n} {}_ip_2}{n} .$$

5. Calculate the sample variance from the relationship

$$s^2 = \frac{\sum_{i=1}^{n} ({}_ip_2 - \bar{x})^2}{n-1} .$$

6. Enter the normal distribution table for the desired confidence, determine the value of $z_{\alpha/2}$, and calculate the confidence limits from the relationship

$$\bar{x} - z_{\alpha/2} \frac{\sigma}{\sqrt{n}} < p < \bar{x} + z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \quad ,$$

where σ is approximated by s.

7. Determine the amount by which the confidence limits must be reduced by calculating the required data length n_{new} from the relationship

$$n_{new} = \left[\frac{\left(z_{\alpha/2} \frac{\sigma}{\sqrt{n}}\right)(\sqrt{n})}{\bar{x}y} \right]^2$$

where

y = % reduction of the confidence interval/100.

<u>Sample Problem (Normal Model)</u>:

Eye movement data are broken into 8 consecutive sample intervals of 20 seconds each. Fixations on instrument number 2 appear typical. Values of p_2 estimated for each sample interval are as follows:

${}_1p_2 = 0.30$	${}_5p_2 = 0.22$
${}_2p_2 = 0.27$	${}_6p_2 = 0.29$
${}_3p_2 = 0.16$	${}_7p_2 = 0.14$
${}_4p_2 = 0.41$	${}_8p_2 = 0.39$

The sample mean and variance are calculated:

$$\bar{x} = \frac{\sum_{i=1}^{n} {}_ip_2}{n} = 0.273 \quad , \quad s^2 = \frac{\sum_{i=1}^{n} ({}_ip_2 - \bar{x})^2}{n-1} = 0.0096, \ \sigma \simeq 0.098 \ .$$

From the normal probability table obtain the α point of a normal distribution for a confidence limit of 80%

$$z_{\alpha/2} = z_{0.1} = 1.282.$$

The confidence limits are

$$0.273 - \frac{(1.282)(0.098)}{\sqrt{8}} < p < 0.273 + \frac{(1.282)(0.098)}{\sqrt{8}} ,$$

$0.229 < p < 0.317$ (chances are 8 out of 10 that the fixations on p_2 will be within the probability interval).

The record length required to reduce the confidence interval to $\pm$ 10% is calculated as

$$n_{new} = \left[\frac{((1.282)(0.098)/(\sqrt{8}))(\sqrt{8})}{(0.10)(0.273)/100} \right]^2 = 21.17$$

and rounding off

$$n_{new} = 22.$$

Consequently, according to this theory, 440 seconds of data should be taken to provide an estimate of p_2 with a confidence interval of $\pm$ 10%.

t Model

Use of the normal model requires knowledge of the population standard deviation σ. If n is large the theory can be applied when σ is unknown, in which case the sample standard deviation s is used. Little is known about the exact distribution of the statistic $\frac{\bar{x} - \mu}{s/\sqrt{n}}$ for small values of n unless the assumption is made that the sample comes from a normal population. If however $\bar{x}$ is the mean of a random sample of size n taken from a normal population having the mean μ and the variance σ^2, then

$$t = \frac{\bar{x} - \mu}{s/\sqrt{n}}$$

is the value of a random variable having the t distribution with the parameter $\nu = n - 1$ (Miller and Freund, 1965). Like the standard normal distribution the t distribution has the mean 0 but its variance depends on the parameter ν, called the number of degrees of freedom.

Thus as in many practical problems when the sample standard deviation is utilized and it is reasonable to assume that sampling is from a normal population, it is possible to construct exact confidence intervals. Therefore $\bar{x} - t_{\alpha/2}\, s/\sqrt{n} < \mu < \bar{x} + t_{\alpha/2}\, s/\sqrt{n}$ gives with a probability of $1 - \alpha$ an exact $1 - \alpha$ confidence interval for μ for random samples of size n where the distribution does not display pronounced departure from normality. Similarly as was shown for the normal distribution model n_{new} can be determined to reduce the confidence interval a specified amount.

The application of the theory to data taking in support of panel redesign assuming a t distribution has the following steps:

1. From a sample of data break the data into n observation intervals of equal length t seconds.

2. Select a typical variable, say p_2, (instrument number 2 fixation times) on which to apply the theory.

3. Calculate the sample probabilities, ${}_ip_2$, where i=1 through the n observation intervals.

4. Calculate the sample mean for the n samples from the relationship

$$\bar{x} = \frac{\sum_{i=1}^{n} {}_ip_2}{n} .$$

5. Calculate the sample variance from the relationship

$$s^2 = \frac{\sum_{i=1}^{n} ({}_iP_2 - \bar{x})^2}{n-1} .$$

6. Enter the t probability table for the desired confidence, determine the value of $t_{\alpha/2}$, and calculate the confidence limits from the relationship

$$\bar{x} - t_{\alpha/2}\frac{s}{\sqrt{n}} < p < \bar{x} + t_{\alpha/2}\frac{s}{\sqrt{n}} .$$

7. Determine the amount by which the confidence limits must be reduced by calculating the required data length n_{new} from the relationship

$$n_{new} = \left[\frac{\left(t_{\alpha/2}\frac{s}{\sqrt{n}}\right)(\sqrt{n})}{\bar{x}y}\right]^2$$

where y = % reduction of the confidence interval/100.

Sample Problem (t Model):

The same problem data given in the sample problem assuming a normal distribution will be used in this example to enable a comparison of the results of the two models. The same mean and variance previously calculated are utilized for this illustration in assuming a t distribution.

Starting at step six of the sequential steps outlined for problem solution the value of $t_{\alpha/2}$ is found from the t probability table

$$t_{\alpha/2} = t_{0.1} = 1.415.$$

The confidence limits are calculated to be

$$0.273 - \frac{(1.415)(0.098)}{\sqrt{8}} < p_2 < 0.273 + \frac{(1.415)(0.098)}{\sqrt{8}} .$$

$0.224 < p_2 < 0.322$ (chances are 8 out of 10 that the fixations on p_2 will be within this probability interval).

The record length required to reduce the confidence interval $\pm$ 10% is calculated as

$$n_{new} = \left[\frac{((1.415)(0.098)/(\sqrt{8}))(\sqrt{8})}{(0.10)(0.273)/100} \right]^2 = 26.3$$

and rounding off

$$n_{new} = 27.$$

Consequently, according to this theory, 540 seconds of data should be taken to provide an estimate of p_2 with a confidence interval of $\pm$ 10%.

The values of the confidence limits and n_{new} for the two sample problems are

Normal Model $\quad n_{new} = 22$

$0.229 < p_2 < 0.317$

t Model $\quad n_{new} = 27$

$0.224 < p_2 < 0.322.$

A comparison of the results for the two models indicates that the t model is more conservative. A major objective of this thesis is to test the hypothesis that the theory has application in the panel redesign problem. The thesis will investigate which of the models provides the best fit to experimental data collected in support of this research.

PROBABILITY DISTRIBUTIONS AND PARAMETER ESTIMATION

When determining the distribution of a random variable such as that of eye movement fixation probabilities, three steps must be followed. First data must be collected and summarized in a frequency distribution. The next step involves calculating or estimating the parameters of the hypothesized distribution. Thirdly, it must be determined whether or not the hypothesized distribution adequately represents the random variable in question. When a plot of the relative frequency distribution has been obtained selection of appropriate probability distribution functions becomes a matter of experience and judgment. Once one or more distribution classes have been identified as potential, a determination of the numerical values of the distribution parameters to reduce the distribution class to a specific distribution must be made. An estimate of the sample mean and variance can be obtained from the collected data. Having hypothesized that a random variable is characterized by a probability distribution, it is determined whether the hypothesis, which is at best just an educated guess, is valid.

Statistical inference enables the experimenter to draw conclusions about a large number of events on the basis of observations of a portion of them. This procedure enables testing the hypothesis. Several steps are followed in making a determination of the acceptability of the hypothesis (Siegel, 1956):

1. State the hypothesis.
2. Choose the statistical test for testing the hypothesis.
3. Specify the significance level (α) and the sample size (n).

4. Assume sampling distributions of a statistical type.

5. Define the region of rejection.

6. Compute the value of the statistical test.

In the typical goodness-of-fit statistical test a random sample of data is collected and then a test of the hypothesis conducted that the sample data was drawn from a population of a specified distribution. The Kolmogorov-Smirnov statistical test involves specifying the cumulative frequency distribution which would occur under the theoretical distribution. The point at which the largest deviation exists between the theoretical and the observed is calculated. Reference to the sampling distribution of the statistical test indicates whether such a divergence is likely on a basis of chance. If the sampling distribution is less than the observed magnitude then the hypothesis that the data came from the postulated distribution is rejected. The significance level, α , indicates the probability that the statistical test will yield a value under which the hypothesis will be rejected when in fact it is true. The above procedure will be employed in the analysis of the data collected in this research.

The objective of the experiment was to collect data to determine eye movement fixation probability estimates for fixed length segments of time and to test the hypothesized distribution they follow. The data would later be utilized to investigate the proposed models for record length estimation.

This research was conducted in the Human Factors Laboratory at Virginia Polytechnic Institute and State University. The experiment enabled the recording of eye movement data of various subjects who were monitoring random signal inputs to four instrument meters. A more complete description of the hardware apparatus and the actual procedures utilized in conducting the experiment follows.

Figure 1 contains a block diagram of the data gathering system. Photographs of the experimental facility are shown in Figures 2, 3, and 4. Eye movement data were collected utilizing 8 mm movie film. Four meter instruments and the motion picture camera were mounted as shown in Figures 3 and 4 at an approximate three foot viewing distance from the subject. The camera was located in the center of the panel behind a half mirror. A KODAK Instamatic M-12 8 mm movie camera recorded eye movements. This fixed focus camera was equipped with a 14 mm f/2.7 KODAK EKTANAR lens and had a shutter speed of approximately 1/40 second. A TIFFEN type +1 close-up lens was fitted on the camera to provide a sharp picture at a viewing distance of approximately 33 inches. High speed super 8 color film, KODAK EKTACHROME 160 (Type A), was utilized.

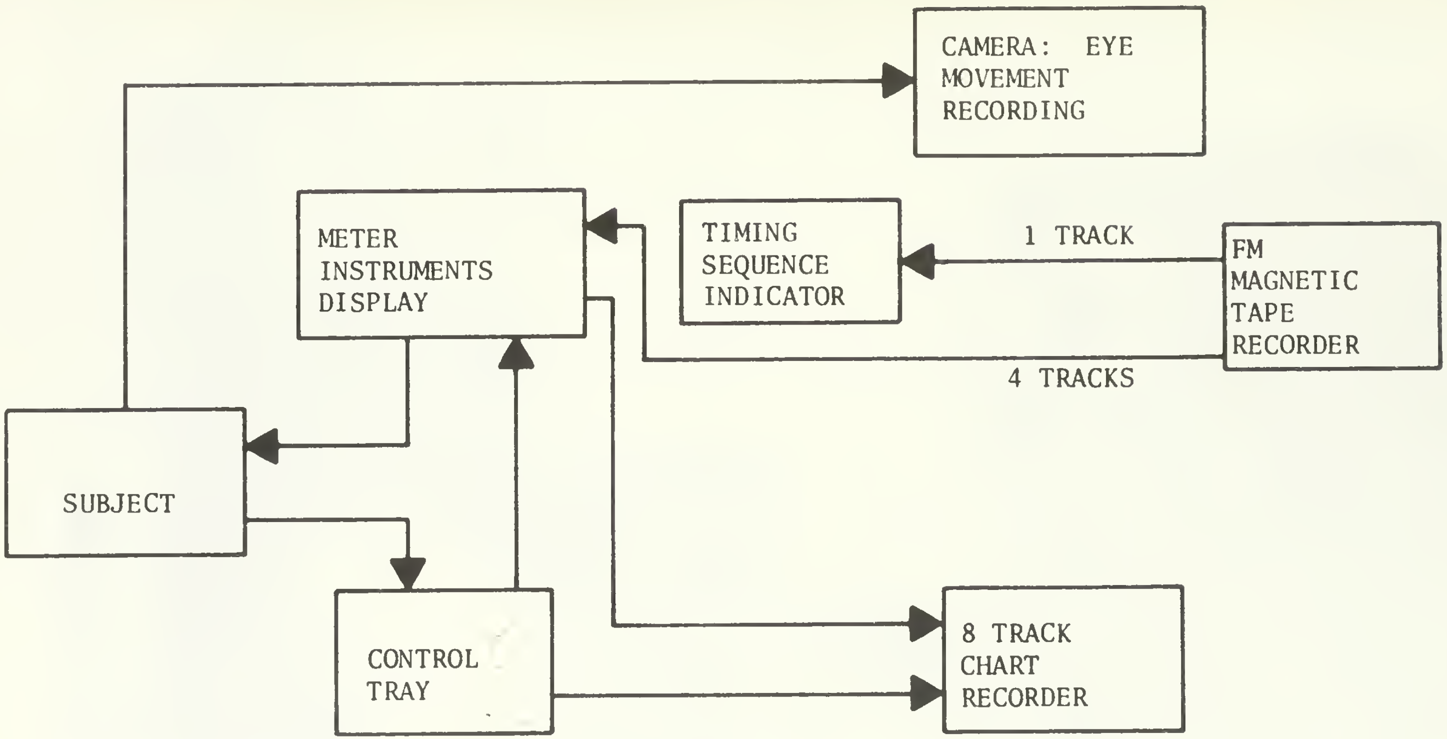


Figure 1. Block Diagram of Experimental Setup

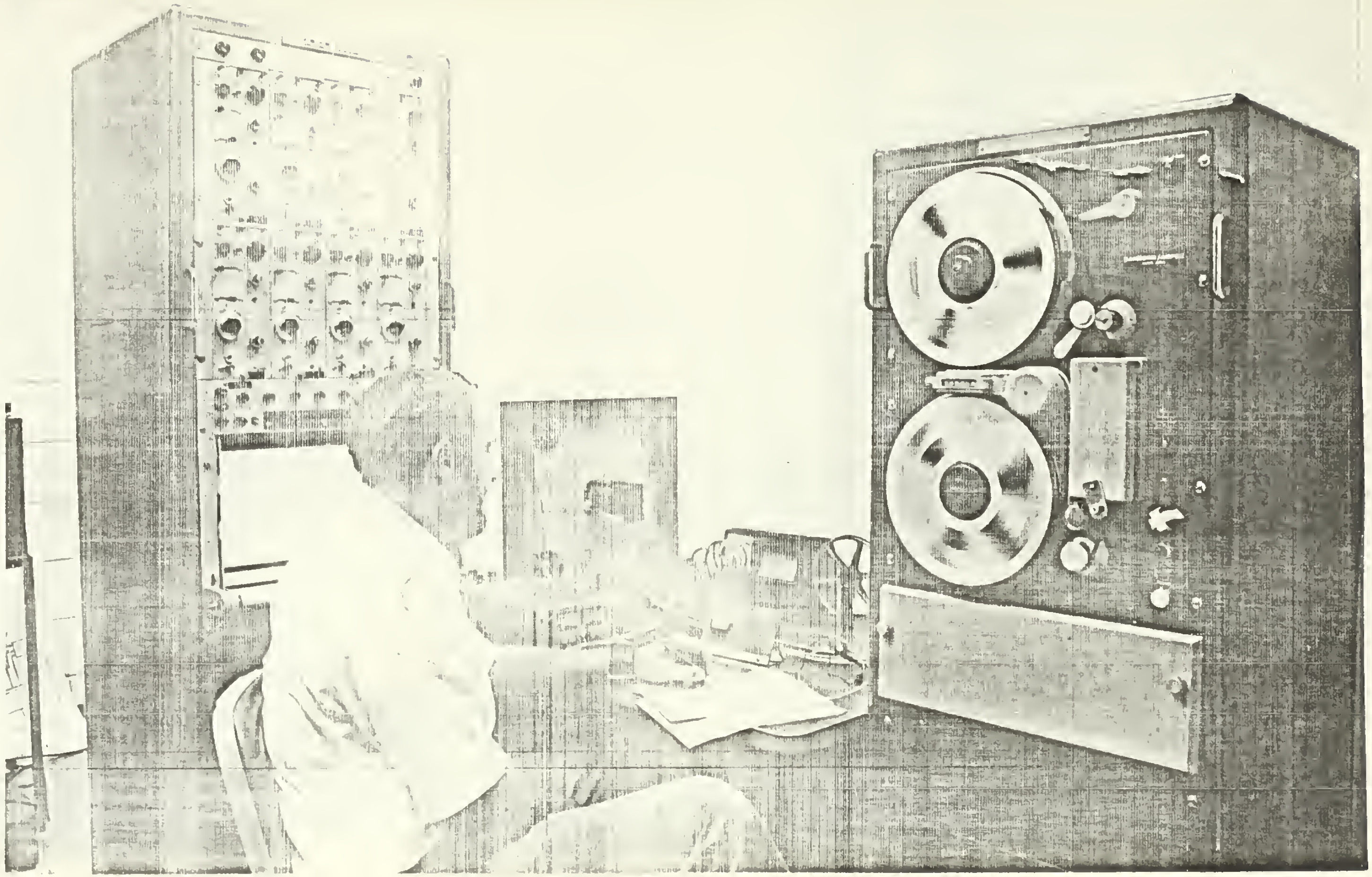


Figure 2. Experimenter Position with Associated Hardware

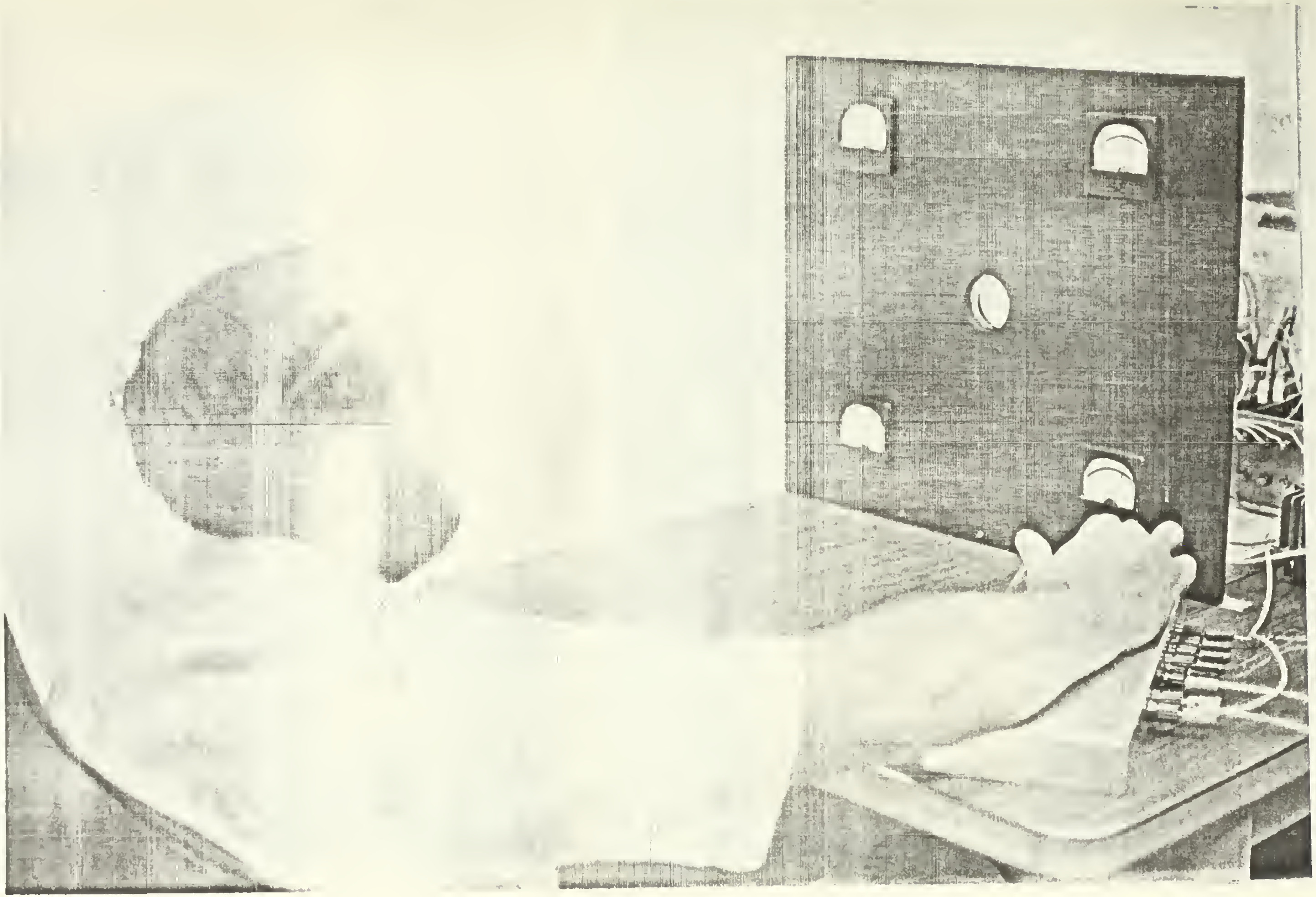
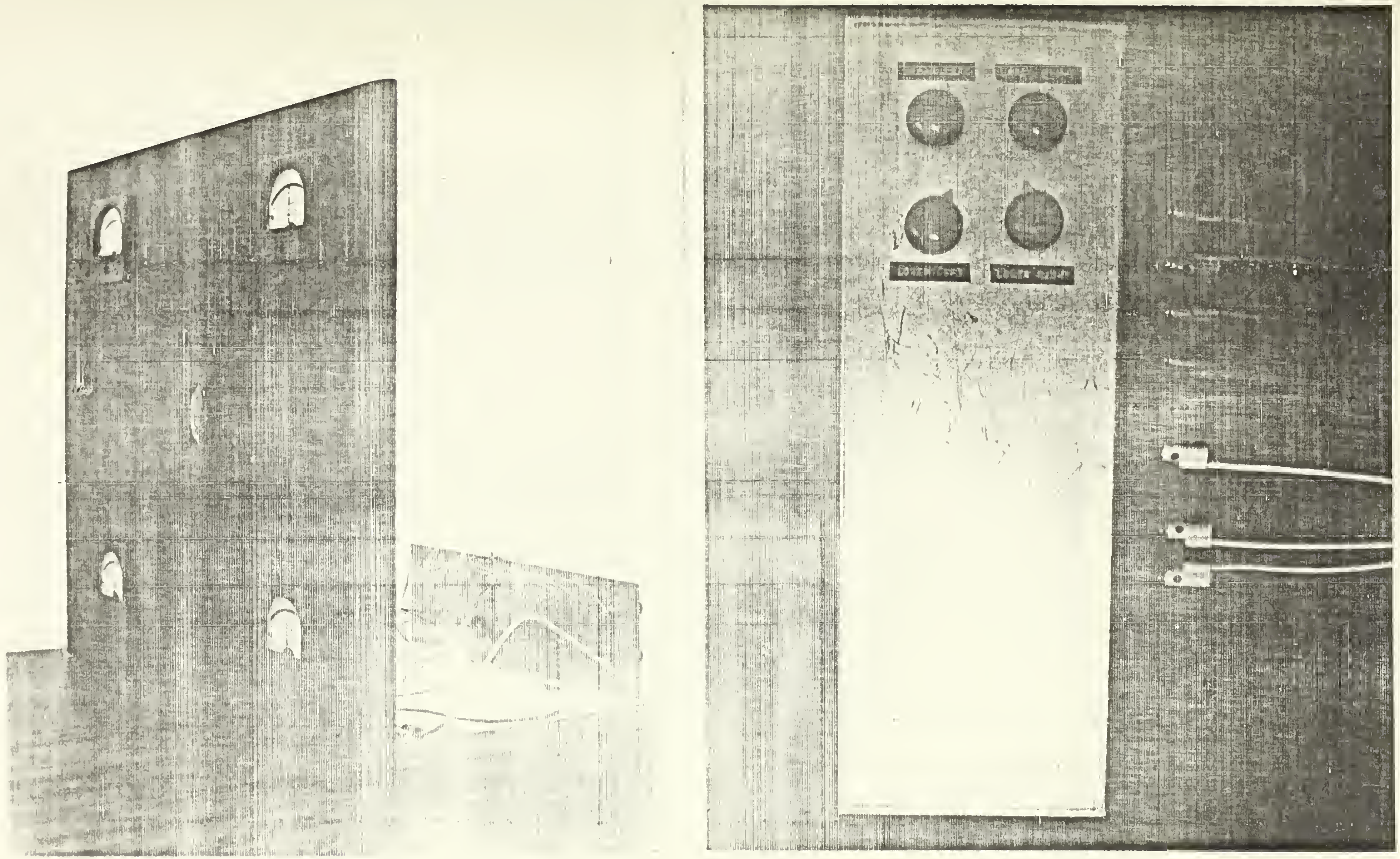


Figure 3. Subject Position with Associated Hardware



Display Panel

Control Tray

Figure 4. Close up of Panel and Tray

Random input signals previously recorded on four tracks of a FM magnetic tape provided the error signal inputs to the four meters. These signals were generated by a white noise signal generator, passed through a low pass filter and taped for use in conducting the experiment. The spectral density of the signal produced by the noise generating circuit was

$$\psi(w)=G(jw)G(-jw) = \frac{-K^2 w^2}{(1+w^2)(1+6.25w^2)(1+400w^2)}$$

where w is the radian frequency variable and K^2 is an amplitude constant. A fifth tract provided timing signals to the experimenter in conducting the experiment. This enabled each subject to experience identical input signals to the four meters during the experiment and ensured that the data collected for analysis covered the same input signals for all subjects participating in the experiment.

The subjects were required to null an error when one was observed on a meter. An error was considered to occur when the meter pointer was displaced outside of a color coded green tolerance area marked on the meter face and was located in a red color coded area located approximately thirty degrees to the right and left of the meter pointer vertical. The nulling procedure was accomplished by the subject's right hand operating one of the four 1K potentiometer controls shown in Figure 4. The operation and physical arrangement of these potentiometers eliminated the need for their direct viewing when being operated.

The error nulling procedure performed by the subject merely furnished the subject with something to do and provided a sense of accomplishment in completing the desired task. A wiring schematic for the experiment is shown in Figure 5. During the four minute segment of the taped

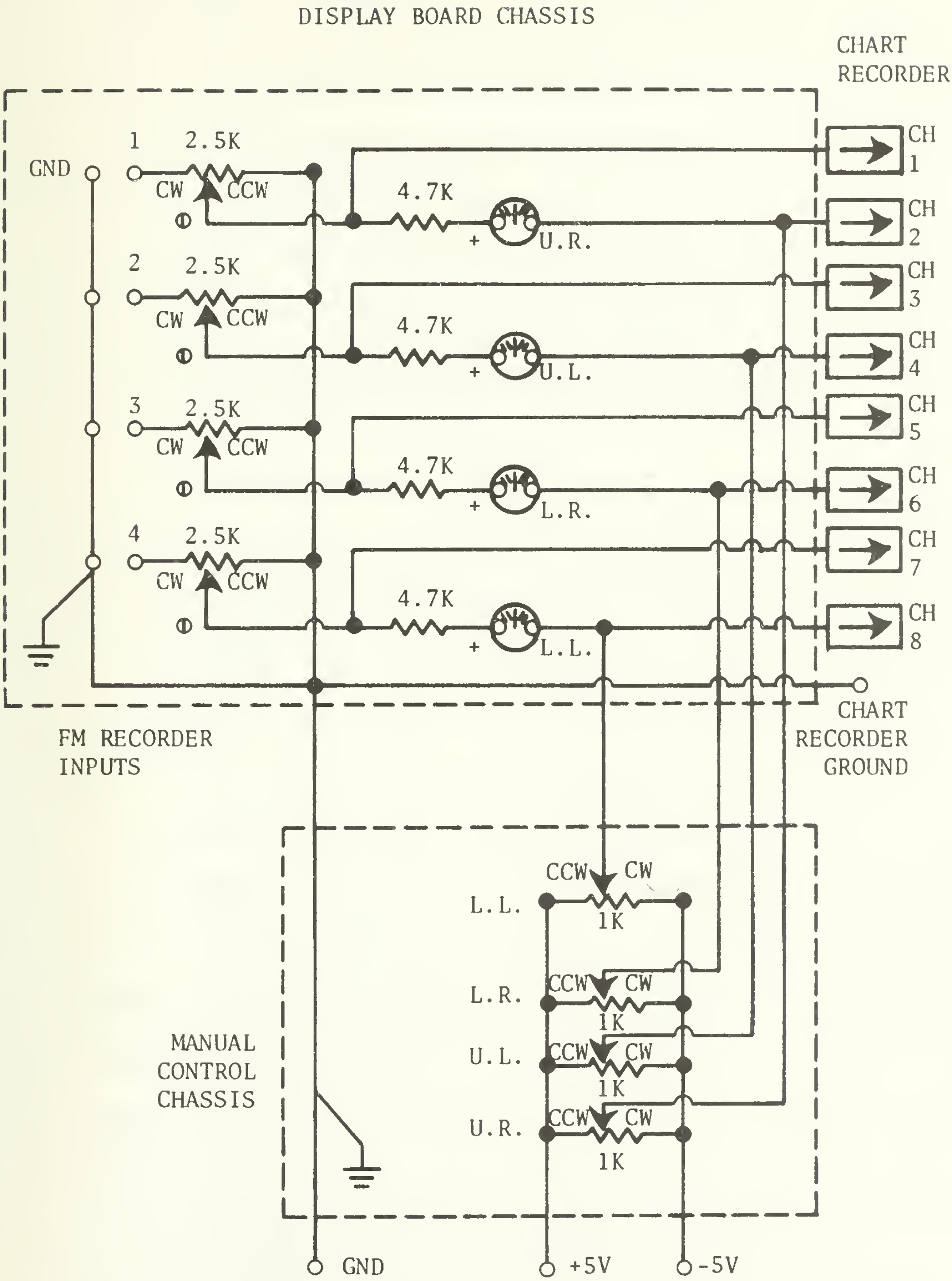


Figure 5. Experimental Facility Wiring Diagram

random input signals used for data collection, the 2.5K potentiometers were initially adjusted so that the meters would read out of tolerance the following percentages of the four minute period

Upper Left	50%	Lower Left	40%
Upper Right	30%	Lower Right	15%.

Of course, these values assume no corrections are made by the subject.

A standard brief and practice session was given to each subject prior to the actual data collection run. Emphasis was made on scanning all instruments through eye movement. Head movement was not constrained. This ensured a more natural scanning procedure by the subjects. Four minutes of continuous eye movement data were recorded for each of the subjects.

Ten different student volunteer subjects, ranging in age from 20 to 26 years were utilized to collect data. Of the ten subjects two were female. Each subject, upon arrival, was asked to read a set of general instructions (Appendix B) after which questions concerning the written instructions only were answered by the experimenter. The subject was then seated in front of the instrument display panel and the seat height was adjusted as required for optimum photographic conditions. All subjects were right handed and their forearm placed comfortably on top of the control panel. Subjects were informed that they would be given a five minute practice run, during which time they were to get the feel of the equipment operation. At the end of the practice run each subject was given a two minute rest period. After the rest period the subject was given another minute of practice which led directly into a four minute data collection run. No communication was conducted with the subjects during the data acquisition portion of the experiment.

As stated, ten subjects participated in the experiment to collect data on operator eye movement. Data were lost on two subjects: one due to a camera malfunction during the data recording phase of the experiment and the other due to a misunderstanding of the instructions provided to the subject. The data for the remaining eight subjects included that of the two female participants. Approximately 3,600 frames of eye movement data were collected on film for each of the eight subjects. A frame by frame analysis, utilizing an 8 mm movie film viewer, enabled the transformation of the raw film data into a format required for the investigation. No difficulty was encountered in utilizing the viewer. The results of the film analysis were considered very accurate. The four instruments which the subjects were viewing on the instrument panel were identified for the analysis as follows

A. Upper Left

B. Upper Right

C. Lower Right

D. Lower Left.

From the total number of frames of data obtained from each subject, 3,520 frames were utilized in the analysis. A determination of what instrument the subject was viewing in each frame of film was made and recorded. When the eyes of the subject were observed to be in a transition from one instrument to another, the subject was considered for analysis purposes to be viewing the acquiring instrument. The identification of the acquiring instrument was determined by advancing the film in the viewer by two frames. This philosophy provided consistency

in the analysis. In a few cases where determination of what the subject was viewing was impossible it was recorded separately as noise for later consideration.

Initially the data were broken into 64 intervals of 55 frames each, for a total of 3,520 frames for each subject. This procedure was conducted for each of the eight subjects over corresponding segments of the raw film data. Over each of the 64 intervals the average number of frames that the subjects viewed each of the four instruments, A, B, C, and D, was calculated and the first order probability of the respective instrument being viewed was determined. Of the 512 intervals of 55 frames analyzed for the eight subjects, noise was identified in 48 intervals. Of these 48 intervals, 23 contained one frame of noise, 22 contained two frames of noise and three contained three frames of noise. The resultant first order probabilities associated with noise were insignificant and were disregarded in the remainder of the investigation. The effect this procedure had was to cause the sum of first order probabilities in those intervals where noise occurred to be slightly less than unity. Having obtained the first order eye movement fixation probability estimates for fixed length segments of time in each of the 64 intervals, histograms of the frequency distribution of the random variable were plotted for each of the four instruments.

Initial consideration in the number of frames comprising each interval and the total number of intervals allowed straightforward calculations in doubling the interval size (i.e., halving the total number of intervals). Thus, histograms were determined for the eight subject average data not only for 64 intervals but also for 32 and 16 intervals.

In plotting the histograms 14 bins were utilized to cover the full range of first order probabilities that might possibly have been encountered (Appendix C).

In addition to the data on the eight subject average the same analysis procedures were performed on a randomly selected subject, subject number seven.

Typical of the frequency distribution found are those depicted in Figures 6 through 15. The mean and variance was calculated for each of the 24 conditions investigated and are found in Table 1.

Having summarized the data in a frequency distribution reasonable guesses regarding the distribution of the eye fixation probability estimates for fixed length segments of time were made. Initial consideration was given to the Poisson distribution; however since the mean and variance for this distribution must be equal and the data clearly indicated this not to be the case, this discrete probability distribution was rejected. The following continuous probability distributions were considered: normal, a normal approximation of the gamma (Appendix D), and the uniform distributions. The uniform distribution was primarily considered to determine if the goodness-of-fit test that was to be conducted would discriminate sufficiently between the hypothesized continuous distributions.

The Kolmogorov-Smirnov goodness-of-fit test was conducted. A tabulation of the test results is found in Table 2 for the eight subject average and Table 3 for subject number seven. As the results indicate, in only two cases did the goodness-of-fit test fail and the associated hypothesis had to be rejected (subject number seven, 64 interval, gamma

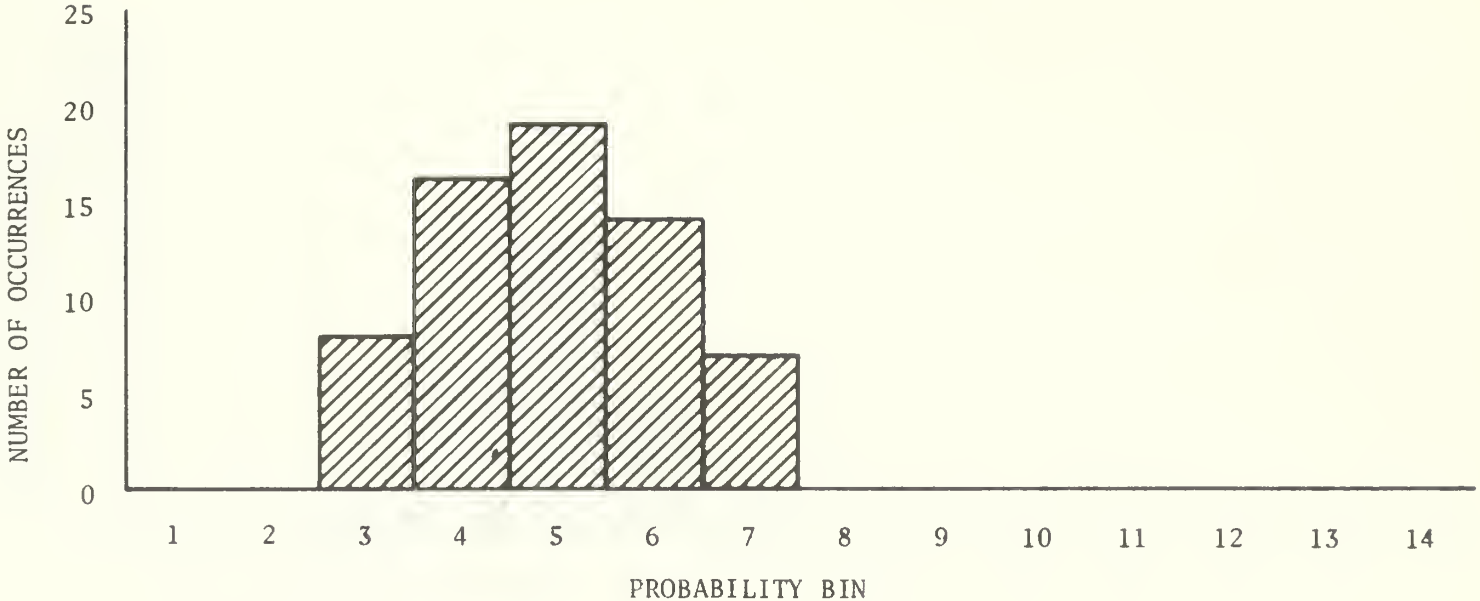


Figure 6 . Frequency Distribution: Eight Subject Average, Instrument A, 64 Intervals

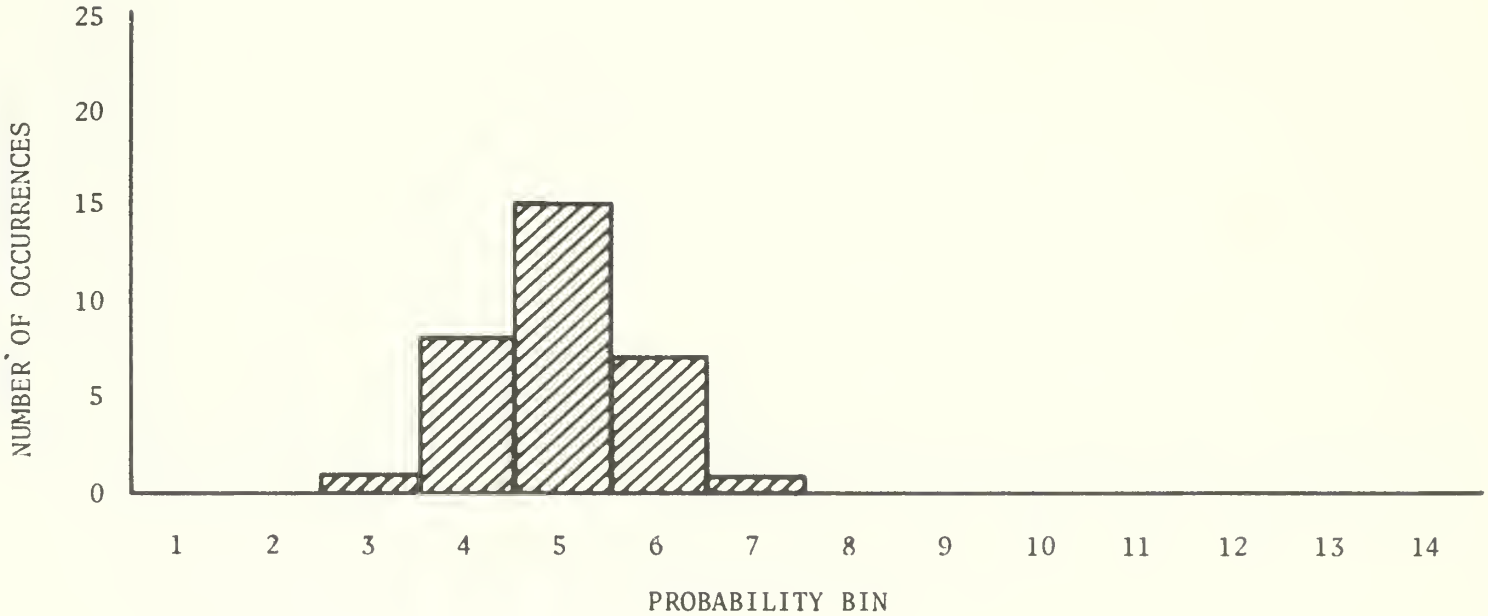


Figure 7. Frequency Distribution: Eight Subject Average, Instrument A, 32 Intervals

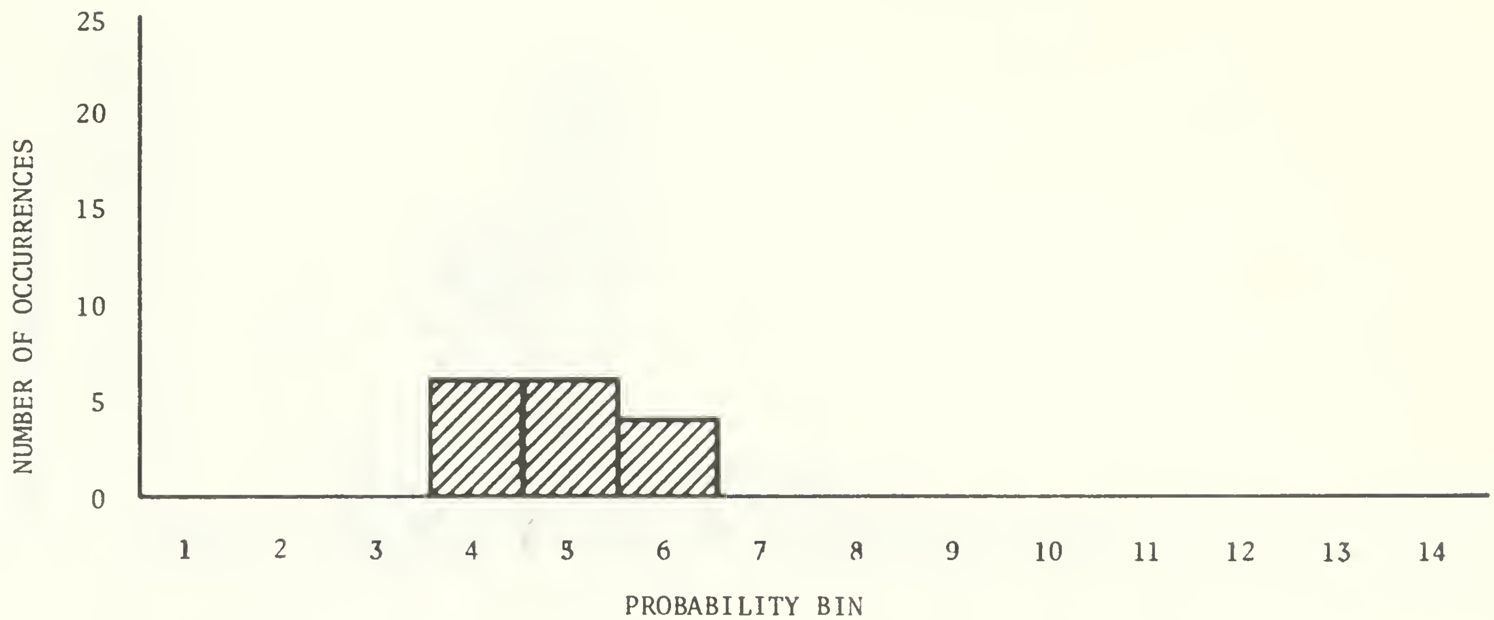


Figure 8. Frequency Distribution: Eight Subject Average, Instrument A, 16 Intervals

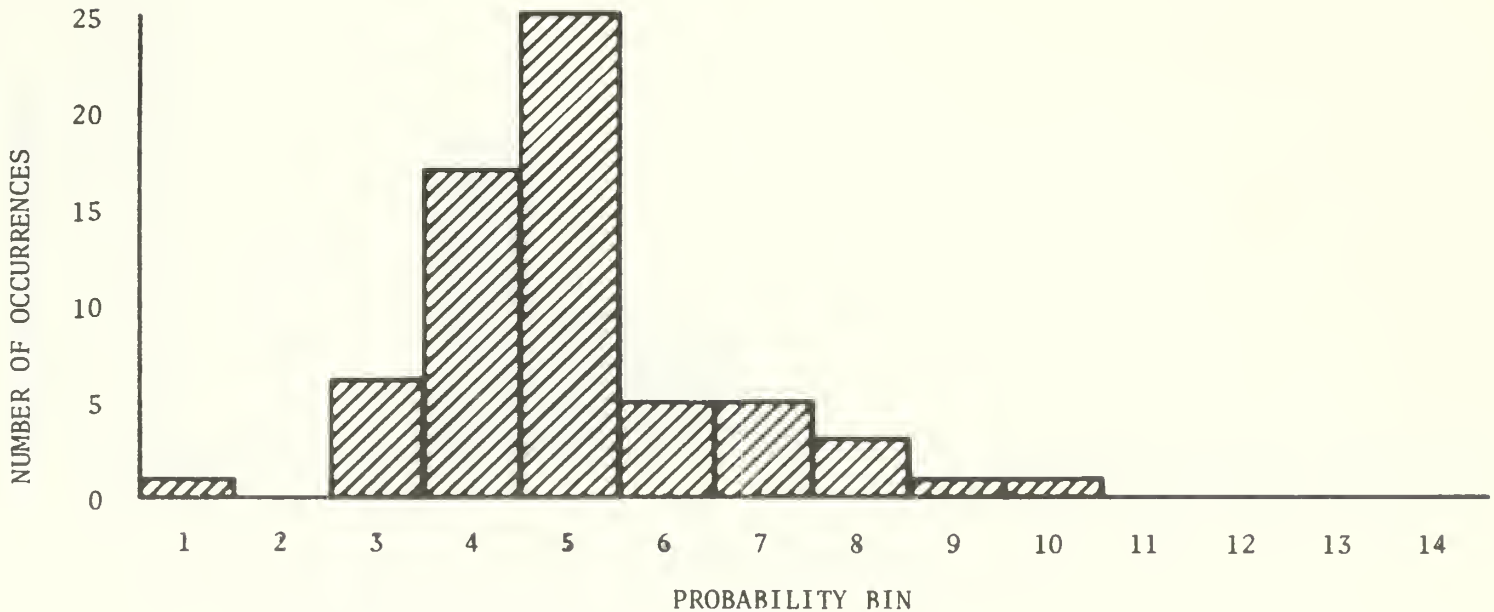


Figure 9. Frequency Distribution: Subject Number Seven, Instrument A, 64 Intervals

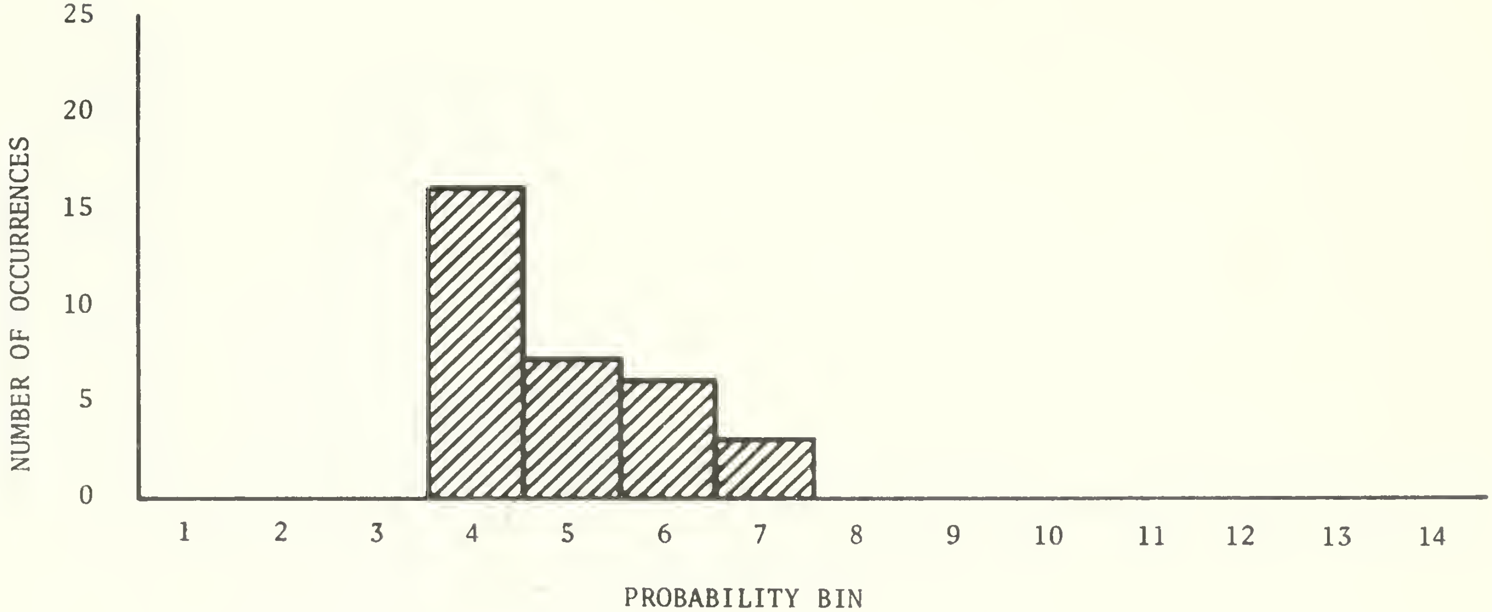


Figure 10. Frequency Distribution: Subject Number Seven, Instrument A, 32 Intervals

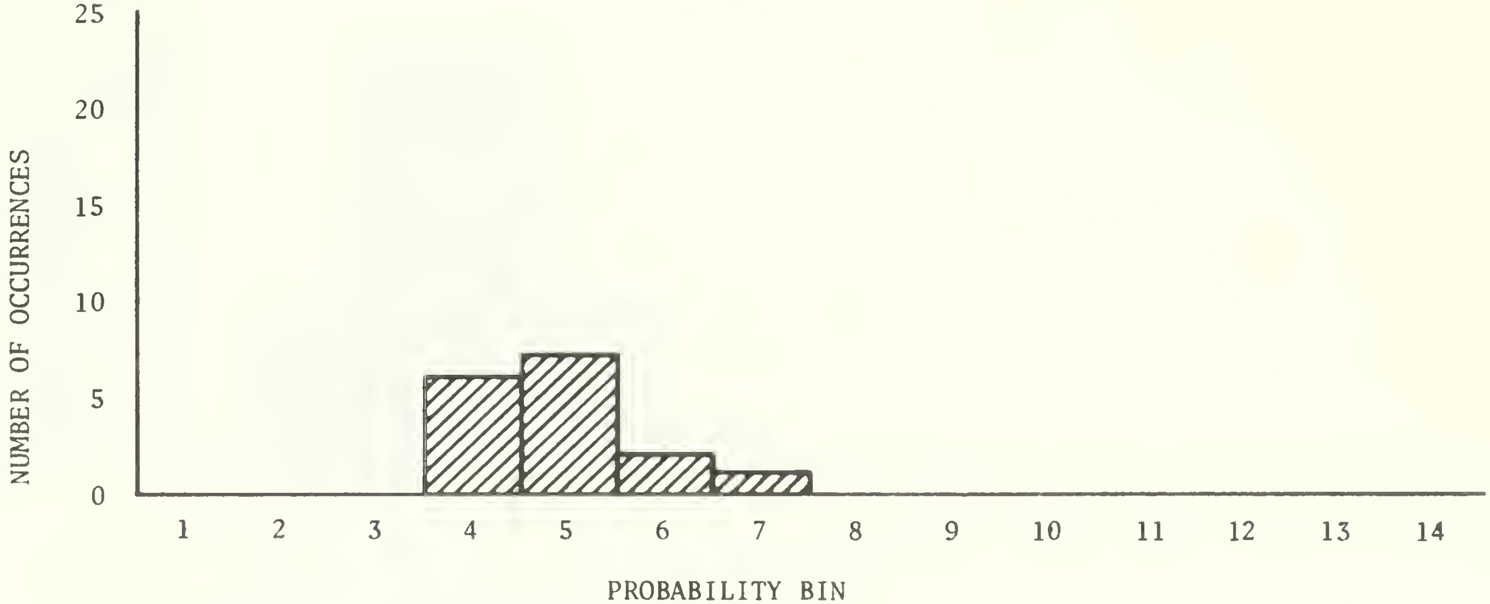


Figure 11. Frequency Distribution: Subject Number Seven, Instrument A, 16 Intervals

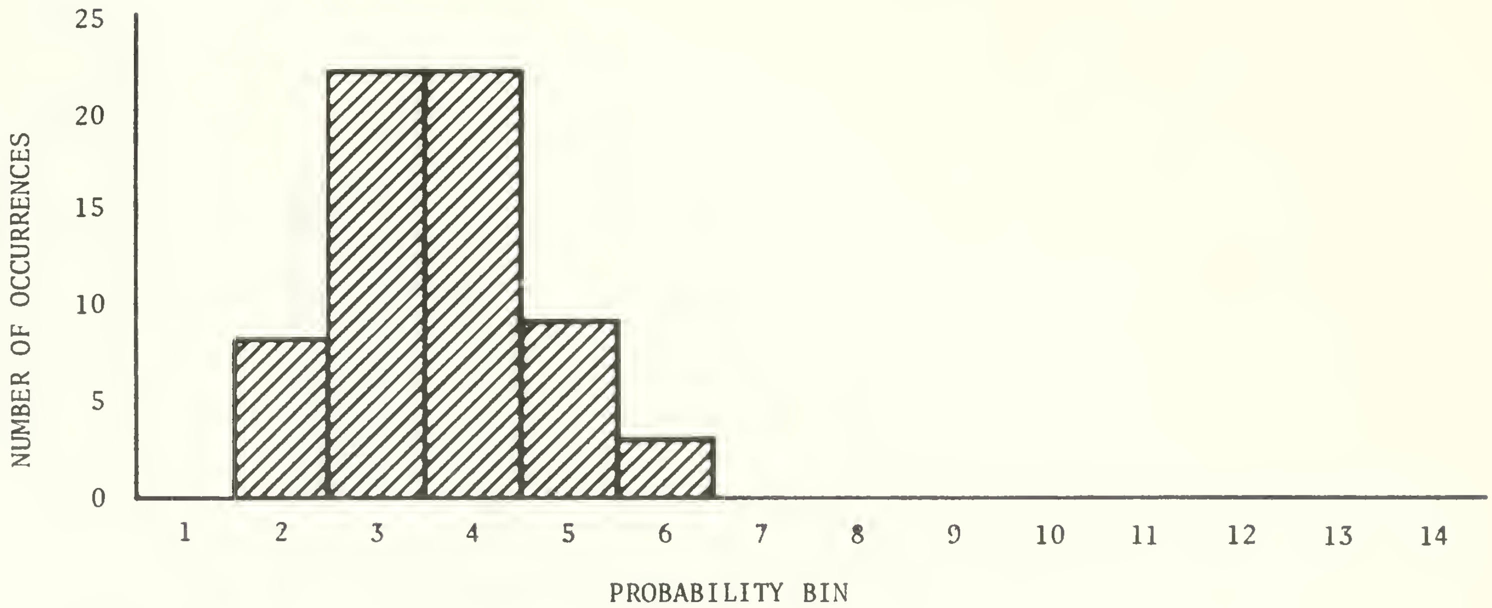


Figure 12. Frequency Distribution: Eight Subject Average, Instrument C, 64 Intervals

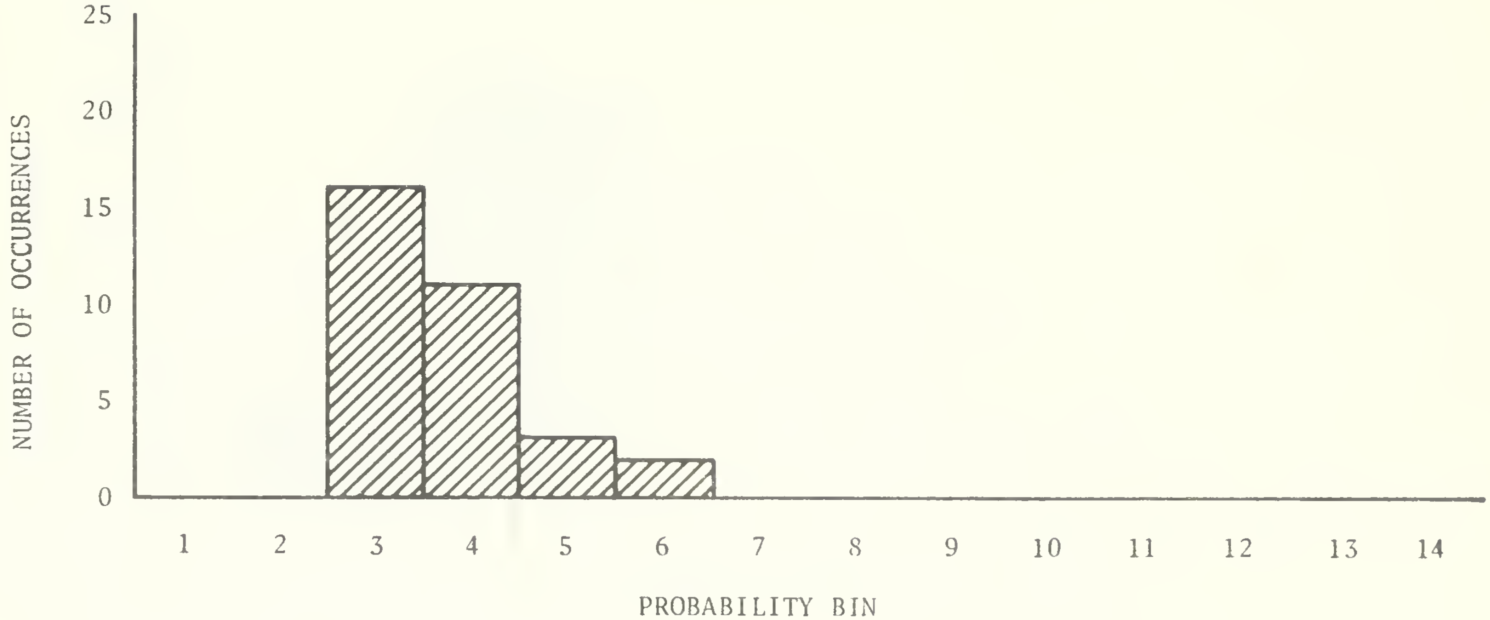


Figure 13. Frequency Distribution: Eight Subject Average, Instrument C, 32 Intervals

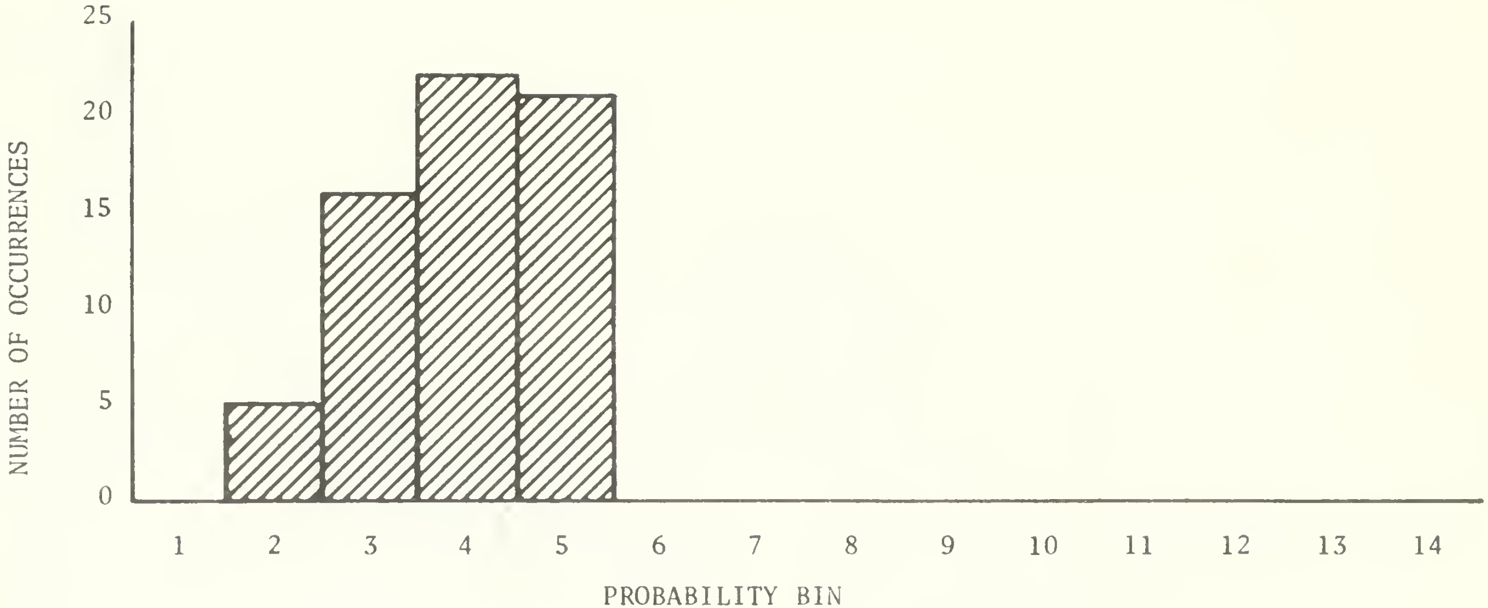


Figure 14. Frequency Distribution: Subject Number Seven, Instrument D, 64 Intervals

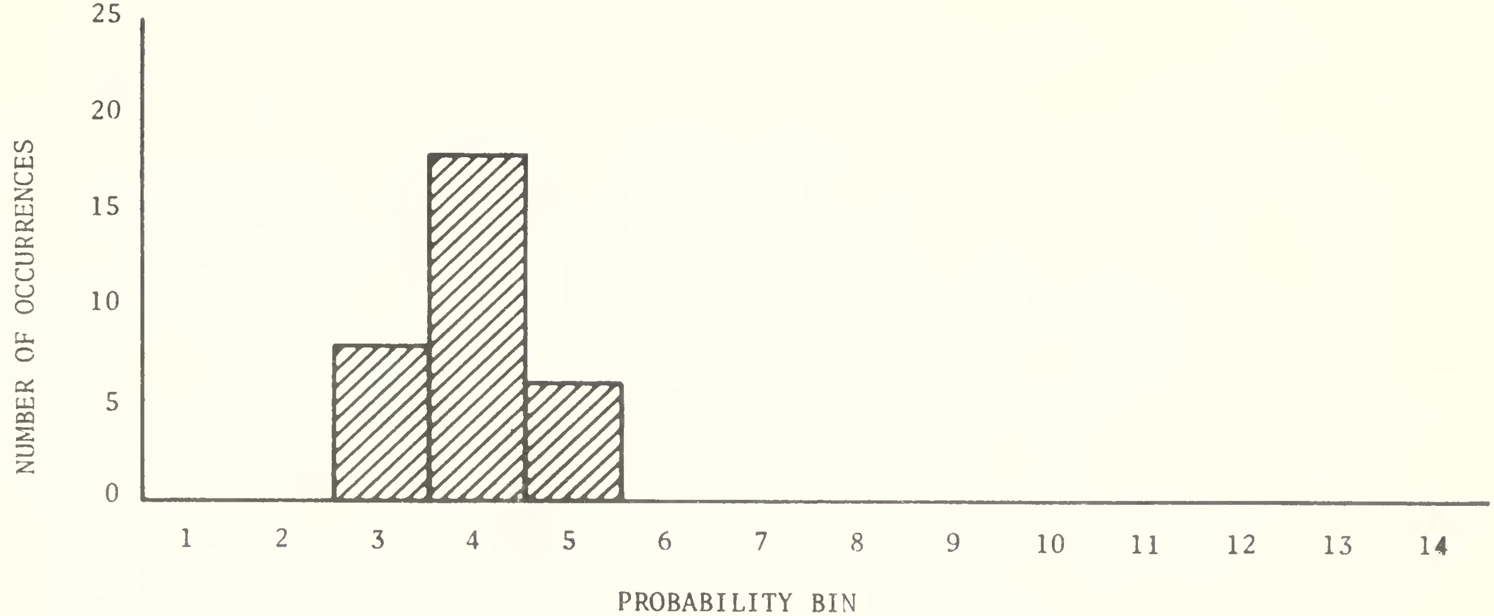


Figure 15. Frequency Distribution: Subject Number Seven, Instrument D, 32 Intervals

TABLE 1. Experimental Values of the Mean and Variance

Number of Intervals	Instrument	Eight Subject Average		Subject Number Seven	
		Mean	Variance	Mean	Variance
64	A	0.32061	0.00675	0.31391	0.01211
	B	0.22968	0.00512	0.22471	0.00581
	C	0.22847	0.00454	0.21590	0.00763
	D	0.21807	0.00495	0.24147	0.00467
32	A	0.32060	0.00438	0.31732	0.00579
	B	0.22874	0.00278	0.22471	0.00224
	C	0.23500	0.00383	0.21307	0.00318
	D	0.21813	0.00219	0.24147	0.00200
16	A	0.32060	0.00256	0.30044	0.00416
	B	0.23467	0.00143	0.22471	0.00130
	C	0.23500	0.00208	0.21307	0.00195
	D	0.21812	0.00131	0.24147	0.00097

TABLE 2. Summary of Results of the Kolmogorov-Smirnov Test for the Eight Subject Average

Number of Intervals	Instrument	D_{max} Values of Hypothesized Cumulative Distributions: Normal	Gamma	Uniform
64	A	0.0393	0.0861	0.0512
	B	0.0851	0.0974	0.0593
$D_{0.95} = .17$	C	0.0518	0.0647	0.0652
	D	0.0367	0.1190	0.0822
32	A	0.0408	0.0936	0.0900
	B	0.0729	0.1083	0.0946
$D_{0.95} = .24$	C	0.1330	0.1068	0.1072
	D	0.0192	0.0837	0.0270
16	A	0.1297	0.0773	0.0741
	B	0.0361	0.0594	0.0322
$D_{0.95} = .328$	C	0.0532	0.0912	0.0081
	D	0.1043	0.0414	0.0928

Since $D_{max} < D_{0.95}$ for all cases, any one of the distributions could be used to describe the variable. However, since the value of D_{max} is more consistently least in the normal distribution it would be best to utilize the normal distribution to describe the variable.

TABLE 3. Summary of Results of the Kolmogorov-Smirnov Test for Subject Number Seven

Number of Intervals	Instrument	D_{max} Values of Hypothesized Cumulative Distributions: Normal	Gamma	Uniform
64	A	0.1132	0.1806 (Fail)	0.1512
	B	0.0792	0.1693	0.1277
$D_{0.95} = .17$	C	0.0456	0.2201 (Fail)	0.1024
	D	0.0698	0.1519	0.0571
32	A	0.1609	0.1329	0.1198
	B	0.0386	0.1214	0.0652
$D_{0.95} = .24$	C	0.0709	0.1749	0.0688
	D	0.0259	0.0852	0.0749
16	A	0.0591	0.1186	0.1145
	B	0.0508	0.0303	0.0507
$D_{0.95} = .328$	C	0.0690	0.0414	0.0841
	D	0.1133	0.0831	0.0435

For the normal distribution $D_{max} < D_{0.95}$ for all cases and the value of D_{max} is more consistently least. The Gamma distribution fit failed the test for two cases (64 interval, instruments A and C).

test, instruments A and C). In the majority of cases the normal hypothesis provided the best fit to the experimental data. It was thus concluded that the normal hypothesis could not be rejected and it provided the best fit of the distributions tested.

Similarly an additional determination of fit was made by summing up the absolute differences from the hypothesized distribution and the experimental data. Tabulated in Tables 4 and 5, again, the normal hypothesis consistently provides the best fit to the experimental data.

TABLE 4. Summary of Results of Absolute Differences of Goodness-of-Fit Test for Eight Subject Average

Number of Intervals	Instrument	Sum of Absolute Differences between Cumulative Hypothesized Distributions and Experimental Data		
		Normal	Gamma	Uniform
64	A	0.0973	0.2594	0.1338
	B	0.1461	0.2580	0.1703
	C	0.1155	0.2203	0.1499
	D	0.1091	0.2929	0.2413
32	A	0.1100	0.1799	0.1651
	B	0.1467	0.2510	0.1414
	C	0.2871	0.2156	0.3365
	D	0.0315	0.1507	0.0460
16	A	0.1791	0.1754	0.1145
	B	0.0612	0.1126	0.0467
	C	0.1287	0.1513	0.0141
	D	0.1548	0.1081	0.1553

TABLE 5. Summary of Results of Absolute Differences of Goodness-of-Fit Test for Subject Number Seven

Number of Intervals	Instrument	Sum of Absolute Differences Between Cumulative Hypothesized Distributions and Experimental Data		
		Normal	Gamma	Uniform
64	A	0.3330	0.6386	0.5266
	B	0.1291	0.4646	0.2325
	C	0.1016	0.5609	0.2169
	D	0.1474	0.3627	0.0888
32	A	0.3082	0.3360	0.3126
	B	0.0888	0.1608	0.1577
	C	0.1680	0.1994	0.1499
	D	0.0667	0.1763	0.1019
16	A	0.1721	0.3664	0.2293
	B	0.0795	0.0603	0.0715
	C	0.1717	0.1056	0.1632
	D	0.1300	0.0859	0.0691

ESTIMATING RECORD LENGTH

Next in the analysis was the application of the experimental results to models of record length estimation discussed in the section, Theoretical Models for Estimating Record Length. Since the normal hypothesis could not be rejected and consistently provided the best fit to the experimental data, it was assumed that sampling was from a normal population. Two models of record length estimation were investigated: the normal, assuming that the experimental data mean and variance were without error and the t model, assuming the standard deviation was unknown and the sample standard deviation must be used.

Tolerance on the mean, as a percentage of the mean, were calculated for three segments of experimental data, each of six intervals (55 frames per interval) and projected to a full 64 intervals by the previously developed relationships

for the normal distribution,

$$\text{tolerance on the mean} = z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \left(\frac{\sqrt{n}}{\sqrt{n_{new}}} \right) \qquad \text{and}$$

for the t distribution

$$\text{tolerance on the mean} = t_{\alpha/2} \frac{s}{\sqrt{n}} \left(\frac{\sqrt{n}}{\sqrt{n_{new}}} \right) .$$

These tolerances were compared with actual tolerances on the mean obtained from the full 64 intervals of experimental data. Interval segments (n) used were data intervals 1 through 6, 31 through 36, and 51 through 56. This procedure was conducted for instruments B and C on the experimental data for the eight subject average, subject number three and subject number seven. A 0.80 confidence interval was used in determining values

for $z_{\alpha/2}$ and $t_{\alpha/2}$.

As the results indicate in Tables 6, 7, and 8, the tolerances on the mean calculated for the three six intervals of data and projected to the full 64 intervals provide a conservative estimate of the actual tolerances on the mean found for the full 64 data intervals. The t model assumption results were more conservative than that for the normal population assumption.

TABLE 6. Eight Subject Average Tolerance of the Mean Values

Distribution	Instrument	64 Intervals	Tolerance of the Mean Intervals Indicated and Projected to 64 Intervals (n_{new}) 1-6	31-36	51-56
Normal	B	0.049935	0.055736	0.048749	0.070815
	C	0.047262	0.025820	0.024067	0.075394
Student t	B	0.049935	0.064170	0.056126	0.081532
	C	0.047262	0.029726	0.027709	0.086803

TABLE 7. Subject Number Three Tolerance of the Mean Values

Distribution	Instrument	64 Intervals	Tolerance of the Mean Intervals Indicated and Projected to 64 Intervals (n_{new}) 1-6	31-36	51-56
Normal	B	0.093575	0.116450	0.087931	0.089592
	C	0.132976	0.110660	0.166167	0.119356
Student t	B	0.093575	0.134071	0.101239	0.103150
	C	0.132976	0.127405	0.191312	0.137417

TABLE 8. Subject Number Seven Tolerance of the Mean Values

Distribution	Instrument	64 Intervals	Tolerance of the Mean Intervals Indicated and Projected to 64 Intervals (n_{new}) 1-6	31-36	51-56
Normal	B	0.054390	0.134750	0.080956	0.109285
	C	0.064849	0.019581	0.069406	0.095934
Student t	B	0.054390	0.155141	0.093205	0.125823
	C	0.064849	0.022544	0.079909	0.110452

CONCLUSIONS

The theory developed by Wierwille, based on the hypothesis that operator eye fixation probability estimates for fixed length segments of time follow a normal distribution, cannot be rejected based on the experimental results obtained herein. The theory enables the application of known statistical concepts widely used in engineering to the problem of record length estimation for taking data in support of panel redesign. In gathering data from a preliminary design configuration the following steps should be followed in support of the redesign effort:

1. From the data sample break the data into n observations of equal length t, where an appropriate value of n is six.
2. Select a typically used instrument on which to apply the theory.
3. Calculate the sample probabilities for each of the n observation intervals.
4. Calculate the mean of the n sample probabilities.
5. Calculate the sample variance.
6. Enter the normal or t distribution tables and calculate confidence limits (t distribution assumption is more conservative than the normal assumption).
7. Determine the amount by which the confidence limits must be reduced.
8. Calculate the required data length n_{new}.

Thus the design engineer is able to calculate an estimate of the required data length to obtain an accurate estimate of the probability of fixation or link values.

The major contribution of the research conducted has been the experimental validation in one situation of a general technique for handling the problem of data taking in support of layout of instrument panels utilized in dynamic man-machine systems. The analysis has also demonstrated the stability of human operator data and a procedure for the estimation of record length to obtain certain desired accuracies in panel design. The procedures developed provide a tool to the system or design engineer that assist in the determination of optimum instrument panel configuration early in the design process.

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APPENDIX A

Relationship Between First and Second Order Probabilities

Lij = link value between instruments i and j

$p_{ij} + p_{ji} = K_o Lij \Big|_{i \neq j}$ where K_o is an arbitrary constant

Lii is not defined

Lij is a non-normalized link value

The link value probability is given by the relationship

$$p_{Lij} = \frac{Lij}{\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} Lij} ,$$

where N = number of instruments and

$$\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} p_{Lij} = 1.0 \quad . \tag{1}$$

The sum of all off diagonal probabilities of a probability matrix is given by

$$p_{ij} + p_{ji} = K_1 p_{Lij} \tag{2}$$

$$\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (p_{ij} + p_{ji}) = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} K_1 p_{Lij} \quad .$$

The sum of all probabilities of a probability matrix minus the main diagonal probabilities is

$$\sum_{i=1}^{N} \sum_{j=1}^{N} p_{ij} - \sum_{i=1}^{N} p_{ii} = 1 - \sum_{i=1}^{N} p_{ii} =$$

$$K_1 \sum_{i=1}^{N} \sum_{j=i+1}^{N} p_{Lij} = p_{Lij} \text{ (from relationship (1))}$$

therefore

$$1 - \sum_{i=1}^{N} p_{ii} = K_1 \quad .$$

Substituting into (2) above gives the relationship between second order probabilities and second order link values

$$p_{Lij} = \frac{p_{ij} + p_{ji}}{1 - \sum_{i=1}^{N} p_{ii}} \quad \text{for } i<j$$

$$\text{undefined} \quad \text{for } j>i.$$

Under random scanning but allowing for different frequency of use

$$p_{ij} = p_i p_j$$

$$p_{ii} = p_i^2$$

$$p_{ij} = \frac{2p_i p_j}{1 - \sum_{i=1}^{N} (p_i^2)} \quad .$$

APPENDIX B

Instructions to Subjects

You are about to participate in an experiment that will record your eye movements and control movements. An analysis of these movements and that of other subjects will enable the development of a model which can be used in support of an instrument panel redesign.

You will be seated in front of an instrument panel on which four meters have been mounted. During the performance of the experiment, you are requested to scan these meters. Your head movement need not be constrained. During the running of the experiment, input signals will cause random deflections of the meter pointers. When the pointer is located outside of the color coded green tolerance area - that is in the red region - you are requested to initiate corrective action to bring the pointer back in the green region. Your objective is to maintain as many of the pointers as possible within the green region. This action is accomplished by movement of the respective control potentiometer located on the manual control box. The physical arrangement of the four potentiometers is compatible with the meter arrangement so there is no need to visually verify that you are manipulating the correct control potentiometer.

The camera, which will photograph your eye movement, is mounted in the center of the instrument panel. Please make a conscious attempt not to be distracted from only viewing the four meters.

The total experiment will take approximately fifteen minutes to complete. It will be broken into two segments. The first segment lasting five minutes will consist of a practice run that will enable you to become

familiar with the equipment. Next there will be a two minute rest period. You will then be given another one minute period of practice that will directly lead into a four minute data collection run.

Again, I would like to emphasize that during the performance of the experiment you are asked to perform the following:

1. Scan the four meter instruments.
2. When the pointer of an instrument is out of tolerance, initiate corrective action on the manual control box.
3. Maintain as many of the pointers as possible within the green region.
4. Consciously attempt not to be distracted.

The personnel working on this experiment greatly appreciate your assistance. Do you have any questions?

APPENDIX C

Determination of Bins in Analyzing Data

First Order Probability of Instrument Being Viewed	Associated Bin Assigned
$0 \leq x < 0.07143$	1
$0.07143 \leq x < 0.14286$	2
$0.14286 \leq x < 0.21429$	3
$0.21429 \leq x < 0.28572$	4
$0.28572 \leq x < 0.35715$	5
$0.35715 \leq x < 0.42858$	6
$0.42858 \leq x < 0.50001$	7
$0.50001 \leq x < 0.57144$	8
$0.57144 \leq x < 0.64287$	9
$0.64287 \leq x < 0.71430$	10
$0.71430 \leq x < 0.78573$	11
$0.78573 \leq x < 0.85716$	12
$0.85716 \leq x < 0.92859$	13
$0.92859 \leq x < 1.0$	14

Utilizing the above equal size bins for analyzing the data for the 55 frame interval or a multiple thereof the following is noted:

Number of Frames Viewed in a 55 Frame Interval	Bins Assigned
0 through 3	1
4 through 7	2

8 through 11	3
12 through 15	4
16 through 19	5
20 through 23	6
24 through 27	7
28 through 31	8
32 through 35	9
36 through 39	10
40 through 43	11
44 through 47	12
48 through 51	13
52 through 55	14

Therefore, 0 through 3 counts fall in the first interval, 4 through 7 counts fall in the second interval, etc. With four counts assigned to each interval there is no bias on an individual data frame.

APPENDIX D

Normal Approximation to the Gamma Density

As the gamma density function parameter n increases in value beyond unity the gamma density becomes more substantially bell shaped. Therefore, a normal approximation can be used with relatively small error. Such an approximation simplifies computations associated with fitting the gamma distribution.

To approximate, one procedure is to set the variance of the gamma distribution equal to the variance of the normal distribution and to set the peak value of the gamma distribution equal to the peak value of the normal distribution.

This procedure is developed below, and has been applied in this thesis. The gamma density function is given by the relationship

$$f_x(x_o) = \frac{\lambda}{(n)} (\lambda x_o)^{n-1} e^{-\lambda x_o} \qquad \text{where}$$

mean (m) $= \frac{n}{\lambda}$

variance $(\sigma^2) = \frac{n}{\lambda^2}$

and $x_o > 0$, $\lambda > 0$ and $n < 0$.

The parameters defining the gamma density are calculated from the relationships

$$\lambda = \frac{m}{\sigma^2} \quad \text{and} \quad n = \frac{m^2}{\sigma^2} .$$

The peak of the gamma density is found from the relationship

$$\frac{df_x(x_o)}{dx_o} = 0 = \frac{\lambda}{\Gamma(n)} \left[(\lambda x_o)^{n-1} (-\lambda e^{-\lambda x_o}) + e^{-\lambda x_o} (n-1)(\lambda x_o)^{n-2} \right]$$

and solving for the peak value

$$x_o = \frac{n-1}{\lambda} = \frac{m^2 - \sigma^2}{m} .$$

The normal probability density function is given by the relationship

$$f_{ix}(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{\frac{-(x-m)^2}{2\sigma^2}}$$

Therefore the normal approximation to the gamma density is given by the relationship

$$f_{ix}(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{\frac{-(x-x_o)^2}{2\sigma^2}}$$

where $$x_o = \frac{m^2 - \sigma^2}{m} .$$

VITA

John J. Seeberger, Commander, United States Navy, was born December 5, 1936 in Brooklyn, New York. Upon graduating from Cardinal Hayes High School in New York City in 1954, he entered the United States Naval Academy, Annapolis, Maryland. In 1958, upon graduating from the Naval Academy with a Bachelor of Science in Engineering, he was commissioned an Ensign in the United States Navy and entered pilot training at Pensacola, Florida. As a naval aviator, his flying assignments have primarily consisted of the following: six years of aircraft carrier aviation, two years of land based patrol aviation and three years of test pilot duties. In 1966, he earned a Master of Science in Aeronautical Engineering from the United States Naval Postgraduate School, Monterey, California. He has spent three years in the area of Research and Development of naval aircraft weapon systems. In 1968 he was designated an Aeronautical Engineering Duty Officer in the United States Navy. He is also designated as a qualified Weapon System Acquisition Manager for the Navy. He is currently a member of the Human Factors Society. He entered the graduate school at Virginia Polytechnic Institute and State University, Blacksburg, Virginia in the fall of 1973.

John J. Seeberger

RECORD LENGTH ESTIMATION FOR

TAKING DATA IN SUPPORT OF PANEL REDESIGN

by

John J. Seeberger

(ABSTRACT)

An investigation was conducted on the determination of record length estimation for taking data in support of an instrument panel redesign. The stability of human operator eye movement data and estimation of data record length required to obtain certain desired accuracies in the estimate were experimentally investigated. A model was developed to provide a general technique for finding the optimum design and layout of an instrument panel used in a dynamic man-machine system. The model is based on the assumption that eye fixation probability estimates for fixed length segments of time follow a normal distribution.

Ten subjects participated in the experiment, conducted in a laboratory environment, to collect data on eye fixation probabilities. Various probability distributions were hypothesized with the normal hypothesis consistently providing the best fit to the experimental data.

The procedures outlined provide the system and design engineer with a tool to ensure optimum instrument panel configurations are defined early in the design phase.

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Thesis
S4072 Seeberger
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